NITROGEN REMOVAL EFFICIENCY IN SLAUGHTERHOUSE WASTEWATER BY USING UPFLOW MICROAEROBIC SLUDGE REACTOR

FOO VOON HONG

B. ENG (HONS.) CIVIL ENGINEERING

UNIVERSITI MALAYSIA PAHANG

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

(Student's Signature)

Full Name : FOO VOON HONG

ID Number : AA15090

Date : 30 MAY 2019

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BY USING
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FOO VOON HONG

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ABSTRAK

Kajian terdahulu telah membuktikan bahawa upflow microaerobic sludge reactor (UMSR) mempunyai keputusan yang baik dalam mengubati air piggeri dengan kepekatan ammonium (NH_4^+-N) yang tinggi dan nisbah yang rendah bagi permintaan oksigen kimia (COD) kepada nitrogen total (TN). Dalam kajian ini, satu prototaip UMSR telah dibina untuk merawat air sisa sembelih dengan kepekatan NH_4^+-N yang tinggi dan nisbah COD/TN yang tinggi. Kecekapan penyingkiran nitrogen untuk UMSR kemudiaan dibandingkan dengan loji rawatan air sisa penyembelihan yang sedia ada. Proses aklimatisasi untuk prototaip adalah selama 60 hari. Reaktor dikawal dalam keadaan mikroaerobik yang mana dilarutkan oksigen (DO) adalah dalam lingkungan 0.3 mg/L hingga 1.0 mg/L dan nilai pH adalah dalam julat 7.0-8.0. Sampel influen dan sampel efluen pada hari ke-61, hari ke-65 dan hari ke-70 telah diambil dari prototaip untuk analisis. Sampel influen dan sampel efluen telah diambil dari loji rawatan air sisa Rumah Penyembelihan Kuantan, Pahang untuk berbanding dengan kecekapan penyingkiran nitrogen dengan paramter yang sama. Kadar penyingkiran TN, NH_4^+-N, COD dan permintaan oksigen biokimia (BOD) untuk prototaip adalah 78.28%, 83.57%, 80.59% dan 25.30% masing-masing. Kadar penyingkiran TN, NH_4^+-N, COD dan BOD untuk loji rawatan sedia ada adalah 19.05%, 18.96%, 82.55% dan 9.08% masing-masing. Kesimpulannya, kadar penyingkiran nitrogen untuk UMSR dalam merawat air sisa dengan nisbah COD/TN yang tinggi adalah sangat bagus dan mempunyai prestasi yang lebih baik daripada loji rawatan yang sedia ada.

ABSTRACT

Rapid growth of the livestock industry has led to the increase number of slaughterhouses in Malaysia. The wastewater generated from slaughterhouse will contained a large amount of organic and inorganic pollutants which are harmful to the environment. Previous studies had been proved that upflow microaerobic sludge reactor (UMSR) had excellent results in treating piggery water with high ammonium (NH_4^+-N) and low chemical oxygen demand (COD) to total nitrogen (TN) ratio. In this study, a prototype of UMSR was constructed to treat the slaughterhouse wastewater with high NH_4^+-N concentration and high COD/TN ratio and to compare its nitrogen removal efficiency with the existing slaughterhouse's wastewater treatment plant. The acclimation stage of the prototype was 60 days. The reactor was controlled in the microaerobic condition which the dissolved oxygen (DO) was maintained within the range of 0.3 mg/L to 1.0 mg/L and pH value within the range of 7.0-8.0. Influent samples and effluent samples on Day 61, Day 65 and Day 70 were taken from the prototype for analysis. Influent sample and effluent sample were taken from the wastewater treatment plant of Slaughterhouse Kuantan for the comparison. The average percentage removal rate of TN, NH_4^+-N, COD and biochemical oxygen demand (BOD) of the prototype were 78.28%, 83.57% ,80.59% and 25.30%, respectively. The removal rate of TN, NH_4^+-N, COD and BOD for existing treatment plant were 19.05% ,18.96%, 82.55% and 9.08%, respectively. In conclusion, the UMSR can perform well in treating high COD/TN ratio wastewater and even had better performance than existing treatment plant.

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LIST OF SYMBOLS

RR'NH	Amines
NH_3-N	Ammonia
NH_4^+-N	Ammonium
CO_2	Carbon Dioxide
N_2	Dinitrogen
H_2	Hydrogen
NO_3^--N	Nitrate
NO_2^--N	Nitrite
N_2	Nitrogen Gas
RR'N-NO	Nitrosamines
C_{org}	Organic Carbon

LIST OF ABBREVIATIONS

AerAOB	Aerobic Ammonium-Oxidizing Bacteria
AOB	Ammonia-Oxidizing Bacteria
BOD	Biochemical Oxygen Demand
BNR	Biological Nitrogen Removal
COD	Chemical Oxygen Demand
CMU	Combined Manure with Urine
DO	Dissolved Oxygen
FKASA	Faculty of Civil Engineering & Earth Resources
GDP	Gross Domestic Product
HRT	Hydraulic Retention Time
NOB	Nitrite-Oxidizing Bacteria
STP	Sewage Treatment Plant
SMU	Soaked Manure with Urine
TN	Total Nitrogen
TSS	Total Suspended Solid
UMP	Universiti Malaysia Pahang
UFM	Urine-Free Manure

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In Malaysia, the agriculture sector contributed RM89.5 billion or 8.1% to the Gross Domestic Product (GDP) in 2016. Livestock industry is one of the important sectors which contribute 11.6 % to the GDP of the agriculture sector. (Dept. of Statistics Malaysia, 2017). The growth of the livestock industry was followed by the increase in the number of slaughterhouses. Large volumes of highly polluted wastewater were generated by the slaughterhouses. The wastewater generated from slaughterhouse contains large amounts of organic and inorganic pollutants which are harmful to the environment (Anijiofor and Nik Daud, 2018). One of the common elements in these wastewater is Ammonium (NH_4^+-N), which if discharged without proper treatment can lead to the eutrophication of water bodies (Zhang *et al.*, 2016; Meng, Li, Li, Astals, *et al.*, 2018). Therefore, nitrogen removal has become one of the notable environmental issues in slaughterhouse wastewater treatment.

Generally, biological nitrogen removal (BNR) process is known as the combined process of nitrification and denitrification. Nitrification is known as a microbial process to oxidize the nitrogen compounds by the nitrifiers from the form of NH_4^+-N to nitrite (NO_2^--N) and nitrate (NO_3^--N). The nitrification process is accomplished by two groups of autotrophic nitrifying bacteria which are ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). Autotrophic bacteria are defined as a type of bacteria that can build organic molecules by using energy obtained from inorganic sources. During the nitrification process, AOB plays its role to oxidize the NH_4^+-N to NO_2^--N. Then NOB will further oxidize NO_2^--N to NO_3^--N (American Water Works Association, 2002). Besides that, another key process in BNR is denitrification. Throughout the denitrification process, the oxidized forms of nitrogen will be converted to dinitrogen

(N_2) or its lesser extent, nitrogen gas (N_2) (Ni *et al.*, 2017). Nitrification is an aerobic process while denitrification is an anaerobic process. One of the common engineered treatment technologies for treating wastewater is the anaerobic-aerobic combined process but it required high treatment cost and low treatment efficiency where the process is required to be carried out in two different reactors (Meng, Li, Li, Sun, *et al.*, 2016).

Microaerobic treatment process has been introduced for treating wastewater in recent decades. It has the advantages in producing low amount of excess sludge, lesser treatment cost, effective chemical oxygen demand (COD) removal rate and occupying lesser space (Zheng and Cui, 2012). Microaerobic is defined as a transitional state between aerobic and anaerobic conditions. It's dissolved oxygen (DO) concentrations are ranging from 0.3 mg/L to 1.0 mg/L, aerobic and anaerobic bacteria are allowed to coexist in the same activated sludge reactor (Zitomer, 1998; Zhang *et al.*, 2018). In the sludge flocs, the aerobic, anaerobic and facultative bacteria can live in different depths according to their needs towards oxygen (Zheng and Cui, 2012). Aerobic bacteria such as AOB, NOB and heterotrophic aerobic bacteria crave oxygen, therefore they live in the outer layer of the activated sludge. The outer layer of the sludge floc has a relative abundance of DO concentration while DO concentration deep in the sludge floc is to the contrary. The oxygen consumption of the aerobic bacteria cause DO concentration deep in the sludge floc to become relatively low or nearly zero. However, anaerobic microbes such as denitrifiers and anaerobic fermentation bacteria are suitable to live in this condition (Meng, Li, Li, Sun, *et al.*, 2016). In previous studies, microaerobic treatment process has proven that the nitrogen removal efficiency for domestic wastewater with low COD/TN ratio is as high as 80% (Zheng and Cui, 2012; Zhang *et al.*, 2018)

In the present study, an upflow microaerobic granular sludge reactor (UMSR) with falling water and reflux prototype is constructed to investigate nitrogen removal efficiency of the microaerobic treatment process towards slaughterhouse wastewater with high COD/TN ratio. The comfortable conditions for denitrification has been suggested as the COD/TN ratio of 6.0-8.0 (Obaja *et al.*, 2003). However, there were no studies on the microaerobic treatment process towards wastewater with high COD/TN ratio. 6 major parameters will be considered in the analysis which are TN, NH_4^+-N concentration, NO_2^--N concentration, NO_3^--N concentration, biochemical oxygen demand (BOD) and COD. pH and DO concentration will be observed every day during the acclimation stage of the inoculum sludge and controlled within the suitable range. Nitrogen removal efficiency of the prototype will be deduced from all these 6 parameters. It is believed that the microaerobic treatment process is favourable for the slaughterhouse wastewater treatment. The nitrogen removal efficiency of the UMSR will be compared with that of the existing treatment plant using the same parameters.

1.2 Problem Statement

Large volumes of wastewater will be discharged to the water bodies due to the development of the agricultural sector and rapid industrialization in Malaysia. Wastewater produced from slaughterhouses is characterized by high organic content such as nitrogen and phosphorus (Anijiofor and Nik Daud, 2018). Nitrogen exists in various forms in the wastewater. It can be in organic form such as NH_4^+-N or inorganic forms which included NO_2^--N and NO_3^--N (Yaakob et al., 2018). Nitrogen components are one of the common contaminants in wastewater which can cause eutrophication to occur on the surface of water bodies (Zhang et al., 2016; Meng, Li, Li, Astals, et al., 2018). Proper treatment process should be implanted before the slaughterhouse wastewater is discharged to the water bodies. In fact, there are no standards available for ammoniacal nitrogen discharge in Malaysia. Removal of ammoniacal nitrogen is not a design criterion for the wastewater treatment plants in Malaysia (Indah Water, 2018).

Two major branches of treatment processes have been introduced for treating the wastewater with high concentration of ammoniacal nitrogen which are biological treatment process and chemical treatment process. In chemical treatment process, air-stripping, breakpoint chlorination and ion exchange are the common method to be used. Air-stripping is the volatilization of ammonia gas. Breakpoint chlorination is the addition of chlorine into the wastewater to oxidize the ammonia. Lastly, ion exchange is using a type of clay-clinoptilolite to remove the ammonia. However, these processes will bring negative environmental issues and require high operation cost. Air stripping can cause odour problems, addition of chlorine will need other treatment process to dilute the excess chlorine and ion exchange will be a high operation cost treatment process. In the biological treatment process, aerobic treatment, anaerobic treatment and aerobic-anaerobic combined treatment are the common treatment methods to be used for removal of ammoniacal nitrogen. By comparing to the chemical treatment process, biological

REFERENCES

American Public Health Association, American Water Works Association and Water Environment Federation. (1999). United States, pp. 1-733.

Anijiofor, S. C. and Nik Daud, N. N. (2018) ‘Chicken slaughterhouse wastewater disposal: The challenges ahead’, *Asian Journal of Agriculture and Biology*, 1(42), pp. 42–45. Available at: https://www.asianjab.com/wp-content/uploads/2018/05/6.CHICKE1.pdf.

American Water Works Association (2002) ‘Nitrification’, *U.S. Environmental Protection Agency*, 1(August 15), pp. 1–17. Available at: http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html.

Bernhard, A. (2010) *The nitrogen cycle: processes, players, and human impact*, *Learn Science at Scitable*. Available at: https://www.nature.com/scitable/knowledge/library/the-nitrogen-cycle-processes-players-and-human-15644632 (Accessed: 11 December 2018).

Dept. of Statistics Malaysia (2017) ‘Selected agricultural indicators, Malaysia, 2017’, *Department of Statistics Malaysia Press Release*, 1(22 December 2017), pp. 5–9. doi: 10.1017/CBO9781107415324.004.

EMIS (2015) *Air stripping*, *VITO, Boeretang 200, B-2400 Mol, Belgium*. Available at: https://emis.vito.be/en/techniekfiche/air-stripping (Accessed: 11 December 2018).

Fernández, I., Dosta, J., Fajardo, C., Campos, J.L., Mosquera-Corral, A. and Méndez, R. (2012) ‘Short- and long-term effects of ammonium and nitrite on the anammox process’, *Journal of Environmental Management*. Academic Press, 95(1), pp. S170–S174. doi: 10.1016/J.JENVMAN.2010.10.044.

Hey, D. L. (2001) *Nitrogen pollution: problems, sources, and policy*. Available at: http://seas.umich.edu/ecomgt/pubs/wetlands/hennepin/2.2.PDF (Accessed: 10 December 2018).

Indah Water (2018) *Indah Water Portal*, *Indah Water Konsortium Sdn Bhd*. Available at: https://www.iwk.com.my/do-you-know/sewage-treatment-system (Accessed: 10 December 2018).

Kundu, P., Debsarkar, A. and Mukherjee, S. (2013) ‘Treatment of slaughter house wastewater in a sequencing batch reactor: Performance evaluation and biodegradation kinetics’, *BioMed Research International*, 2013(1), pp. 1–11. doi: 10.1155/2013/134872.

Li, J., Meng, J., Li, J., Wang, C., Deng, K., Sun, K. and Buelna, G. (2016) ‘The effect and biological mechanism of COD/TN ratio on nitrogen removal in a novel upflow microaerobic sludge reactor treating manure-free piggery wastewater’, *Bioresource Technology*. Elsevier Ltd, 209(1), pp. 360–368. doi: 10.1016/j.biortech.2016.05.034.

Meng, J., Li, J., Li, J., Antwi, P., Deng, K., Wang, C. and Buelna, G.. (2015) 'Nitrogen removal from low COD/TN ratio manure-free piggery wastewater within an upflow microaerobic sludge reactor.', *Bioresource Technology*. Elsevier Ltd, 198(1), pp. 884–90. doi: 10.1016/j.biortech.2015.09.023.

Meng, J., Li, J., Li, J., Wang, C., Deng, K. and Sun, K. (2016) 'Effect of seed sludge on nitrogen removal in a novel upflow microaerobic sludge reactor for treating piggery wastewater', *Bioresource Technology*. Elsevier Ltd, 216(1), pp. 19–27. doi: 10.1016/j.biortech.2016.05.034.

Meng, J., Li, J., Li, J., Sun, K., Antwi, P., Deng, K., Wang, C. and Gerardo, B. (2016) 'Efficiency and bacterial populations related to pollutant removal in an upflow microaerobic sludge reactor treating manure-free piggery wastewater with low COD/TN ratio', *Bioresource Technology*. Elsevier Ltd, 201(1), pp. 166–173. doi: 10.1016/j.biortech.2018.08.016.

Meng, J., Li, J., Li, J., Antwi, P., Deng, K., Nan, J. and Xu, P. (2018) 'Enhanced nitrogen removal from piggery wastewater with high NH4+and low COD/TN ratio in a novel upflow microaerobic biofilm reactor', *Bioresource Technology*. Elsevier, 249(November 2017), pp. 935–942. doi: 10.1016/j.biortech.2017.10.108.

Meng, J., Li, J., Li, J., Astals, S., Nan, J., Deng, K., Antwi, P. and Xu, P. (2018) 'The role of COD/N ratio on the start-up performance and microbial mechanism of an upflow microaerobic reactor treating piggery wastewater', *Journal of Environmental Management*. Elsevier Ltd, 217(1), pp. 825–831. doi: 10.1016/j.jenvman.2018.04.029.

Meng, J., Li, J., Li, J., Nan, J., Deng, K. and Antwi, P. (2019) 'Effect of temperature on nitrogen removal and biological mechanism in an up-flow microaerobic sludge reactor treating wastewater rich in ammonium and lack in carbon source', *Chemosphere*. Pergamon, 216(1), pp. 186–194. doi: 10.1016/J.CHEMOSPHERE.2018.10.132.

Ni, B.J., Pan, Y.T., Guo, J.H., Virdisa, B, Hu, S.H., Chen, X.M. and Yuan, Z.G. (2017) *Denitrification processes for wastewater treatment*, *RSC Metallobiology*. The Royal Society of Chemistry. doi: 10.1039/9781782623342-00368.

Obaja, D., Macé, S., Costa, J., Sans, C and Mata-Alvarez, J. (2003) 'Nitrification, denitrification and biological phosphorus removal in piggery wastewater using a sequencing batch reactor', *Bioresource Technology*. Elsevier, 87(1), pp. 103–111. doi: 10.1016/S0960-8524(02)00229-8.

Stephens, A. O. (1970) *Acclimation of activated sludges to industrial wastes*. McMaster University. Available at: https://macsphere.mcmaster.ca/bitstream/11375/20301/1/Stephens_A._O._1970May_Masters..pdf (Accessed: 17 December 2018).

Tripathi, N. (2017) *The disadvantages of ion exchange*, *Leaf Group Ltd.* Available at: https://sciencing.com/disadvantages-ion-exchange-8092882.html (Accessed: 11 December 2018).

Wang, H.Q., Guan, Y.T., Li, L. and Wu, G.X. (2015) 'Characteristics of biological nitrogen removal in a multiple anoxic and aerobic biological nutrient removal process', *BioMed Research International*. Hindawi, 1(1), pp. 1–8. doi: 10.1155/2015/531015.

Watson, S. W., Valois, F. W. and Waterbury, J. B. (1981) 'The Family Nitrobacteraceae', in *The Prokaryotes*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 1005–1022. doi: 10.1007/978-3-662-13187-9_80.

Yaakob, M.A., Radin Mohamed, R.M.S., Al-Gheethi, A.A.S. and Mohd Kassim, A.H. (2018) 'Characteristics of chicken slaughterhouse wastewater', *Chemical Engineering Transactions*, 63(1), pp. 637–642. doi: 10.3303/CET1863107.

Zhang, X., Zhao, B., Meng, J., Zhou, A., Yue, X.P., Niu, Y.K. and Cui, Y. (2018) 'Efficiency, granulation, and bacterial populations related to pollutant removal in an upflow microaerobic sludge reactor treating wastewater with low COD/TN ratio', *Bioresource Technology*. Elsevier, 270(1), pp. 147–155. doi: 10.1016/j.biortech.2018.08.016.

Zhang, Y.M., Wang, X.C., Cheng, Z., Li, Y.Y. and Tang, J.L. (2016) 'Effect of fermentation liquid from food waste as a carbon source for enhancing denitrification in wastewater treatment', *Chemosphere*. Elsevier Ltd, 144(1), pp. 689–696. doi: 10.1016/j.chemosphere.2015.09.036.

Zheng, S. and Cui, C. (2012) 'Efficient COD removal and nitrification in an upflow microaerobic sludge blanket reactor for domestic wastewater', *Biotechnology Letters*, 34(3), pp. 471–474. doi: 10.1007/s10529-011-0801-7.

Zitomer, D. H. (1998) 'Stoichiometry of combined aerobic and methanogenic COD transformation', *Water Research*, 32(3), pp. 669–676. Available at: https://www.sciencedirect.com/science/article/pii/S0043135497002583.